Smart Control of a Thermopile Heat Flux Sensor

A Degree Thesis Submitted to the Faculty of the Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

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by

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Abstract

Nowadays, much of the research that humans carry out is dedicated to discovering the universe that surrounds us. One of these investigations is based on obtaining Venus heat flux. This planet has very high thermal conditions and therefore, any measure must be able to be achieved quickly.

This thesis develops an experiment based on a previous study on how to take this measure by means of thermopiles, heat flux sensors. First simulations are presented, the slowness of the open loop system and the controls proposed to speed up the process. In order to corroborate the correct functioning of these controls, two scenarios have been generated where to do the corresponding tests.

The results obtained confirm that the response time of the closed loop system decreases by a factor 100. Therefore, the use of a control that maintains the constant thermopile gradient and a second control that ensures that thermopile average temperature is equal to surface temperature where to measure is sufficient to obtain a short time of stabilization and measure.

Resum

Avui en dia, gran part de la recerca que els humans duem a terme es dedica a descobrir l'univers que ens envolta. Una d'aquestes investigacions es basa en l'obtenció del flux de calor de Venus. Aquest planeta té unes condicions tèrmiques molt elevades i per tant, qualsevol mesura s'ha de poder aconseguir de forma ràpida.

En aquesta tesi es desenvolupa un experiment basat en l'estudi previ sobre com prendre aquesta mesura mitjançant termopiles, sensors de flux de calor. S'exposen les primeres simulacions, la lentitud del sistema en llaç obert i els controls proposats per agilitzar el procés. Per tal de corroborar el correcte funcionament d'aquests controls s'han generat dos escenaris on fer les corresponents proves.

Els resultats obtinguts confirmen que el temps de resposta del sistema en llaç tancat disminueix en un factor 100. Per tant, l'ús d'un control que mantingui el gradient de la termopila constant i un segon control que asseguri que la temperatura mitjana de la termopila sigui igual a la temperatura de la superfície on fer la mesura són suficient per obtenir un temps d'estabilització i mesura curt.

Resumen

Hoy en día, gran parte de la investigación que los humanos llevamos a cabo se dedica a descubrir el universo que nos rodea. Una de estas investigaciones se basa en la obtención del flujo de calor de Venus. Este planeta tiene unas condiciones térmicas muy elevadas y por lo tanto, cualquier medida debe poder conseguirse de forma rápida.

En esta tesis se desarrolla un experimento basado en el estudio previo sobre cómo tomar esta medida mediante termopilas, sensores de flujo de calor. Se exponen las primeras simulaciones, la lentitud del sistema en lazo abierto y los controles propuestos para agilizar el proceso. Con el fin de corroborar el correcto funcionamiento de estos controles se han generado dos escenarios dónde hacer las correspondientes pruebas.

Los resultados obtenidos confirman que el tiempo de respuesta del sistema en lazo cerrado disminuye en un factor 100. Por tanto, el uso de un control que mantenga el gradiente de la termopila constante y un segundo control que asegure que la temperatura media de la termopila sea igual a la temperatura de la superficie dónde hacer la medida son suficiente para obtener un tiempo de estabilización y medida corto.

Acknowledgements

First of all, I would like to express my gratitude to Manuel Domínguez for accepting me in his lab and guiding me through all this process. All his global vision, advice and experience have made this project possible.

I would also like to thank Lukasz Kowalski for introducing me in laboratory routines, for proportionate me his LabVIEW code and all his help.

Additionally, I want to give special thanks to Eduard Pérez who was very helpful and kind during all my thesis work. Thanks for helping me in the measurements, theory and for spending countless hours trying to understand and solving the problems we were facing. Without him probably I would not have been able to produce al this work.

Finally, I could not finish these acknowledgments without mentioning my parents, brothers, family and friends. Thank you very much for all the trust bestowed on me and all your support during these great 4 years becoming an engineer.

Contents

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1 Introduction

The universe is the totality of the continuous space in which humanity is found, along with all the matter and energy it contains. While the spatial size of the entire universe is still unknown, it is possible to measure the observable universe.

Every day companies as NASA (National Aeronautics and Space Administration) try to find different methods to delve into the universe and reach as maximum knowledge about it as possible. In order to achieve it, lots of probes are prepared every year and some of them are sent to the space to discover and study our solar system.

During these years some probes have reached Venus orbit, thanks to them we were able to know its volume, mass, surface temperature and pressure, composition by volume, etc., but planet heat flux has never been measured.

Heat flux is a flow of energy per unit of area per unit of time [W/m^2]. In steady state, the heat flux is a linear function of the temperature difference across a surface. It allows to study the Venus geology, so knowing this parameter is really important and necessary to learn more about the beginning of our Solar System. This is the reason why JPL (Jet Propulsory Laboratory), which is investigating lots of themes, is taking part in obtaining this parameter, so a new satellite to Venus with new measures to reach is being prepared.

Nowadays on earth, there are lots of applications of heat flux sensors. Ones of the most used for heat flux measurements in the soil as well as through walls and building envelopes that could simulate better a planet surface are the thermopiles HFP01 and HFP03 observed in the figures below.

Figure 1.1: HFP01 heat flux plates.

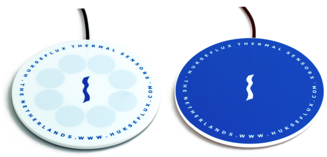

Figure 1.2: HFP03 heat flux plates.

A thermopile is an electronic device that converts thermal energy into electrical one. It is composed by several thermocouples each consisting of two metal alloys electrically connected in series. A single thermocouple will generate an output voltage that is proportional to the temperature difference between its hot and cold joints. Putting thermocouples in series amplifies the signal. In a thermopile heat flux sensor, the hot and cold joints are located at the opposite sensor surfaces.

In the following image a simple structure of the thermopiles used can be observed:

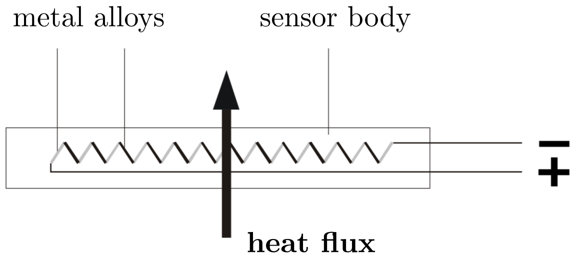

Figure 1.3: Thermopile heat flux sensor general working structure.

The thermopile generates a voltage output proportional to the heat flux through the sensor. This output signal is produced by the thermoelectrical effect, that consists in a combination of Seebeck, Peltier and Thomson effect. These two thermopiles and its behaviour are the ones studied during this thesis.

1.1 Problem statement

Venus temperature of 500 °C has made that only a probe reaches the planet surface. Once in there, it was running just for 45 minutes, so any measure wanted to take from the surface has to be achieved fast.

Measuring Venus heat flux means that once the thermopile reaches the atmosphere it has to touch the planet surface. An ideal response would be that this stabilization proces was instant, so the thermopile output could provide directly the heat flux from the planet. For that reason all the tests and simulations consist in placing the thermopile above a chosen surface, wait till the stabilization process finish and observe the real heat flux.

The studied system is composed by the thermopile in contact with a surface. Its dynamics will present a very slow time response, fact that produces a big transient in open loop measurements.

An open loop result is shown in Figure 1.4 below. This simulation was made considering a constant heat flux to measure of 30 mW/m^2. It is observed that in open loop the response is very slow, it is not yet completely stabilized after 100.000 s, which is exactly what we need to avoid in order to perform a faster measurement of the heat flux.

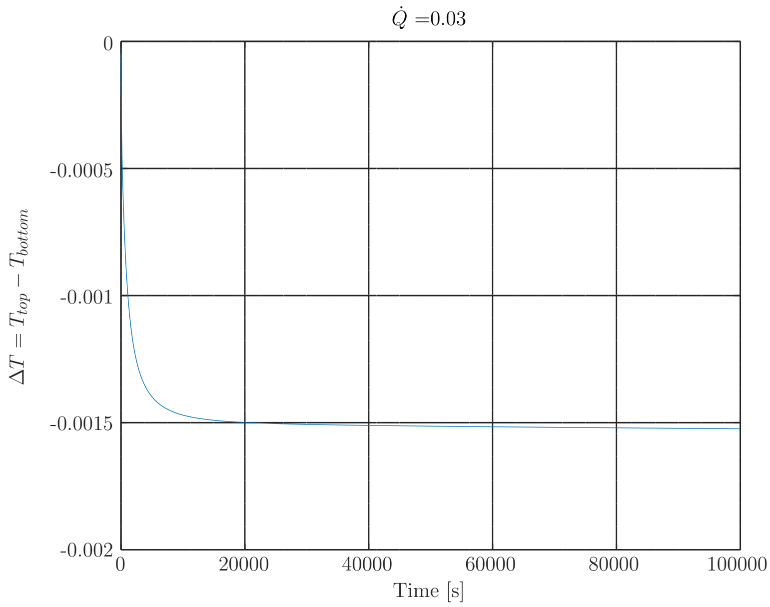

Figure 1.4: Simulated open loop evolution of ΔT = T$_{top}$ - T$_{bottom}$.

In this thesis a control system previously studied will be implemented to reduce the thermopile time response, to help the system to achieve a faster stabilization.

2 Theoretical background

In this second section of the thesis are exposed the proposed controls simulations. All information detailed in the following subsection has been done previous to this work, fact that originated this thesis proposal.

2.1 Previous study

In the beginning of this study it was necessary to know thermopile behaviour so some simulations of it were made. Although our main interest was to observe complete system behaviour, not just internal thermopile dynamics also the effect of thermopile to ground. It was achieved observing the exact moment when thermopile touch the surface. One of the most important simulations of this behaviour has been included in 1.1 Problem statement, where it is observed a slow time response, its waveform stills in settling time at 100.000 s.

The reasons that create this slow response implicate a need of a control system which objective is to guarantee non appreciable change in the complete system when the thermopile is placed on the surface to be measured. This causes that two conditions are needed to be ensured:

- First one is to have a determined constant thermopile gradient.
- Second condition is to accomplish a thermopile bottom temperature as nearby as possible to the one from surface where the thermopile will be placed.

2.1.1 Gradient control

Knowing that, first control proposed consists in controlling thermopile gradient value. Thermopile differential temperature (ΔT_n) is the system input and there is a target gradient value (ΔT_{target}) to reach.

In order to achieve that a pointer described as P_1 will balance the quantity of positive and negative current to inject. It is important to remark that P_1 position will decide the net current for each period injected to the thermopile to guarantee the desired value, so if its value is in the middle it means that current average injection is equal to 0 A. In addition, in the following waveform is observed that a determinated small time of non injection in the end of each period is saved to take the measure.

In this gradient control is taken into account an ideal temperatures matching between surface and thermopile average temperature instants before placing it.

The following scheme shows its first control proposal:

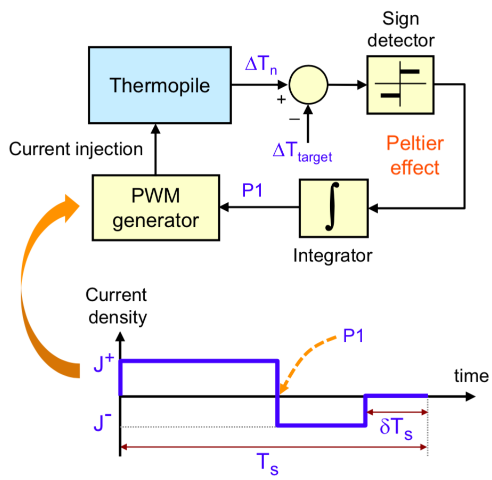

Figure 2.1: Gradient control loop, current waveform injected.

A study of the effect that produces the thermopile in the ground transients is necessary due that this also would affect our system settling time.

Next simulation considers a heat flux to measured of 40 mW/m^2 and 1.000 s after the contact of thermopile with surface. The ground is at 1 m so the 0 is 1 meter depth below it. The simulation represents the temperatures from 0 to 1 meter depth from the surface where the thermopile has been placed. It is shown (at 1 m) that thermopile presence produces a change on temperature ideally not expected and that after 1.000 s this change stills appreciable.

It demonstrate that a second control able to cancel this temperature change when the thermopile is put in contact with the surface is very necessary due to the slow time it would include in the system settling time.

2.1.2 Average control

Second proposal of system control consists in the linked work of both average and gradient controls. So the pointer P_1 continue deciding which is the net current necessary to inject and the new pointer P_2 will control the quantity of current injected in each period in order to decrement or increment thermopile average temperature. This second implementation is necessary to achieve a match between thermopile average temperature and surface temperature before placing it to avoid heat transference between thermopile which provokes transients.

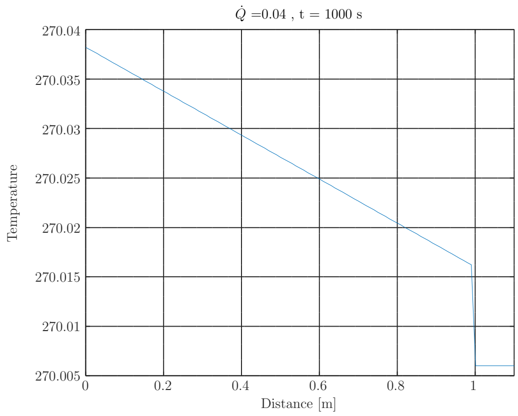

Figure 2.2: Temperature cross section profile.

The following figure shows control loops final proposal:

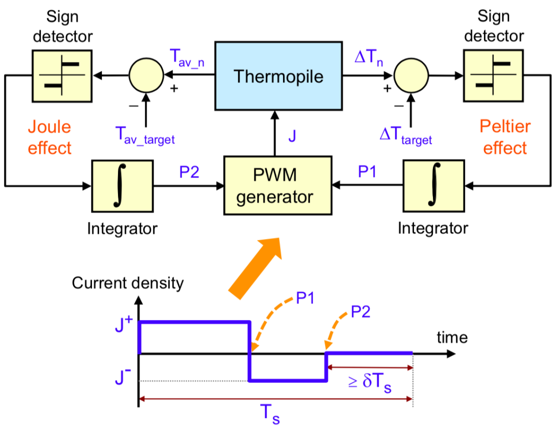

Figure 2.3: Gradient and average control loops, current waveform injected.

3 Work plan and process

In this section is presented all the work done in the thesis before obtaining the final system design. This includes all the tests prepared to understand the thermopile behaviour routines, which help to better introduce active controls proposed.

The following workflow shows the work breakdown structure of my thesis. The theoretical sensor study was needed as I have been working with a device that I had never used before. After the theory study, lots of behaviour tests were a must to perform next steps and finally a final design.

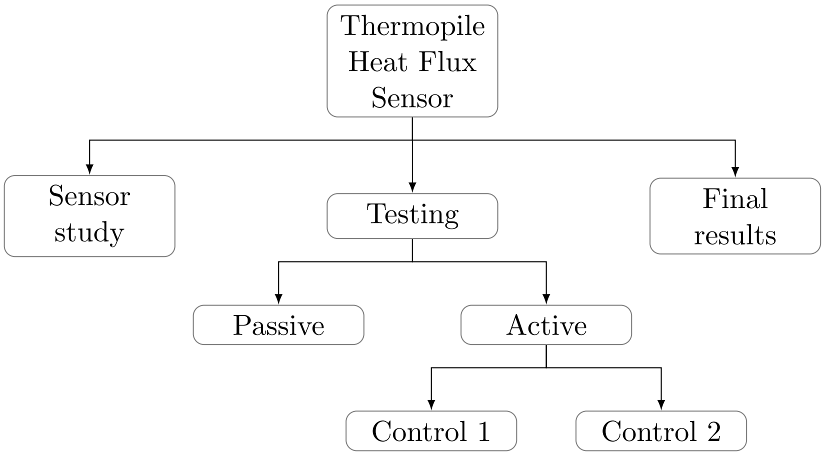

Figure 3.1: Workflow of the thermopile behaviour knowledge.

All relevant methods that have been utilized as well as important measurements to take into account are shown in the next temporal list of tasks made.

First move was reading thermopile manual, accomplish a wide study about all theoretical thermopile aspects to take into account and understanding the simulations given of its behaviour. From all this studies most relevant aspects about thermopile to consider in this project are exposed in the subsection below.

3.1 Theoretical thermopile aspects

Next figure presents the thermopile internal structure. There can be observed different thermocouple (pn) in series, all of them connected to both thermopile surfaces designated as T_{top} and T_{bottom}.

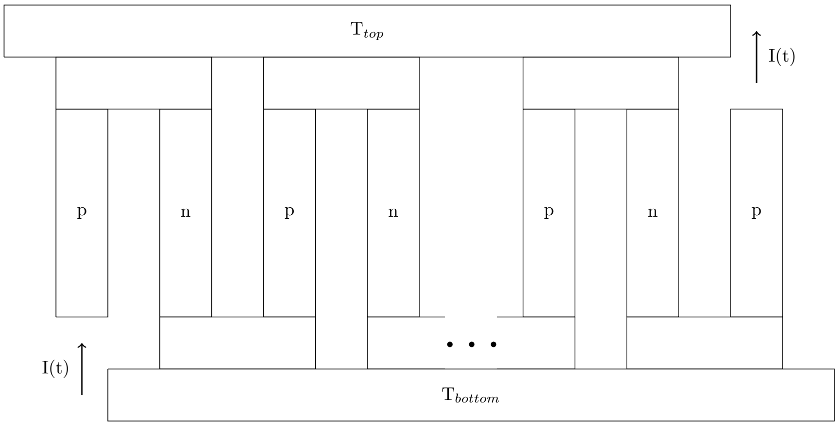

Figure 3.2: Thermopile internal structure.

Taking this image as reference a short overview of thermopile thermoelectric effects will be easily comment. The three effects considered during this project are explained below:

- **Joule effect**

  This effect is not characteristic to the thermopile, it is an origined consequence of injecting current through a component with a non null internal resistance. That current generates an electrons movement inside this resistor and some of its cinethic energy is lost in heat dissipation.

  Given that thermopiles have an internal resistance joule effect is observed. For that reason this effect is exploit in average control where the main objective is to match temperatures between surface and thermopile average temperature.

- **Peltier effect**

  Peltier effect is a thermoelectric property characteristic of thermopiles which states that a temperature difference is created when current goes through it. Injecting current through a thermocouple provokes an electron and hole move that cool or heat its junctions. Electrons or holes direction (up or down) depends on the intensity direction but the movement generated inside p and n will cool or heat the same junction.

  This study allowed to be aware of the Peltier effect explored in the gradient control to maintain the temperature difference between its surfaces (ΔT = T$_{top}$ - T$_{bottom}$).

- **Seebeck effect**

In a complementary way, Seebeck effect states that using a heat source to heat or cool down junctions of pn also provokes the movement of electrons inside the component and so a current.

Seebeck coefficient is used in this thesis to transform the action of controls injecting current to the heat flux value that are generating.

3.2 Thermopile passive state

The thermopile tested is HFP03 (see Figure1.2). A passive behaviour study implies to observe the thermopile output voltage without any excitation. At first the use of a multimeter was necessary to be aware of the output values range and to discover how to take measures correctly.

Conclusions firstly extracted were that both surface behaviours are equals with inverse polarity. Approching something hot to the white plate provides positive output values and spinning the thermopile and repeat the same situation with the blue plate provides negative ones. In addition, thermopile sensitivity is really high so in not controlled ambients achieve heat fluxes under 200 μW/m^2 is unlikely.

During this first tests the internal resistance ($R_{internal}$) calculation was made to know which nominal value has this thermopile. This measure is indirect so it was achieved with the multimeter, turning from voltage to resistance fastly. Two values of output voltage (V_{out_1}, V_{out_2}) and resistance (Z_{in_1}, Z_{in_2}) are needed because multimeter internal intensity (I) isn't known.

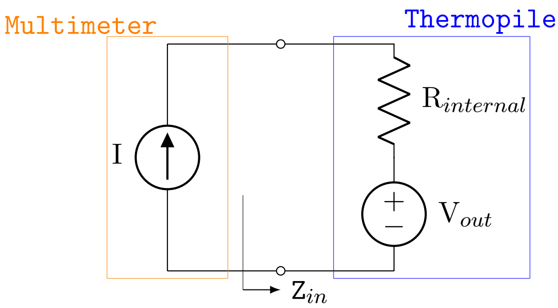

Figure 3.3: Thermopile equivalent circuit in serie with multimeter.

$$R_{internal} = Z_{in_1} - V_{out_1} \frac{Z_{out_2} - Z_{out_1}}{V_{out_2} - V_{out_1}} \tag{1}$$

In ambient temperature the internal resistance is equal to 16,55 Ω. After some tests, I discovered that temperature value range used during this thesis doesn't change much this value, so is not a value to be aware of in following experiments.

Once it done, was time to obtain the results in PC using an FPGA and National Instruments hardware and its software LabVIEW. This program was obtained from a previous work that where differential measures were needed too.

Lots of tests in contact with different temperature surfaces were made and as the thermopile is really sensitive to any heat flux change, every change in the room where I was working was observed. I used a depth book and a box in order to prevent transients generated but it wasn't enough, this system needed a constant heat flux and a controlled ambient to obtain useful results.

Taking into account all these problems found, the first set-up was design and prepared (see 4.1 Set-Up).

3.3 Thermopile active state

The next step was to study thermopile behaviour with different values of current injection. In the following graphic it is observed how intensity affects the value of heat flux measured. The experiment consists in inject 0.1 mA more every 10 minutes starting at 0.1 mA and finishing at 1 mA.

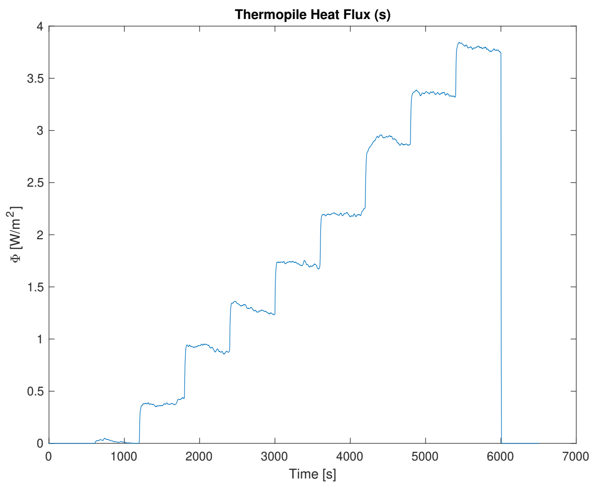

Figure 3.4: Different values of current injection to thermopile.

From this result the implementation of gradient control to the thermopile was instant.

3.4 Test methodology

Before starting a test is necessary to have most similar initial conditions possible. There are conditions like ambient temperature impossible to control, that's why the ones refering to thermopile position or tank door that can be changed have to be taken in care. Thermopile has to be placed in vertical position with its white surface in front of the cylinder and tank door must be closed. Moreover, as in our system there are different transients to consider is really important to also take into account the cylinder heat flux stabilization before any test.

Once all this checks are overcome test can be start, so its time to save every value needed during experiment. After lots of test I realized that waiting just 30 minutes before placing the thermopile in cylinder top surface was enough to know in which initial circumstances is the sensor. In order to observe system response is necessary to wait at least the same after thermopile placement, sometimes in open loop measurements more time is needed. Next scheme shows steps followed in every test:

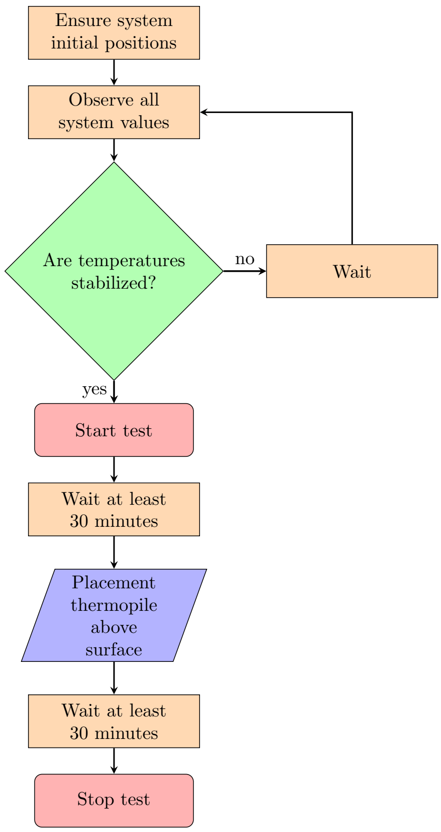

Figure 3.5: Scheme of steps followed in every test.

Since lots of test were made, I had what seemed the final set-up system ideal to simulate the problem state, I knew internal resistance value in working temperature range and also the effect of injecting specific quantities of current.

Final stage of work is set-up assembly and both controls carried out in LabVIEW that will be explained in the following section. There I will inform about some limitations from this first system which are too harmful to the control system implementation, so a new system in other ambient is created from scratch, including hardware and software.

4 System design

This section presents the set-up used in each system designed and its variances. Moreover, it explains the problems encountered and so states the reason of differences between their implemented controls.

4.1 Set-up

In the following two images it is captured general view of first set-up carried out. On the left sytem set-up inside an hermetic tank is observed. Using this container is necessary to avoid in our graphics all fluxes produced by any movement inside the room where it is being tested. Its external view can be seen on the right.

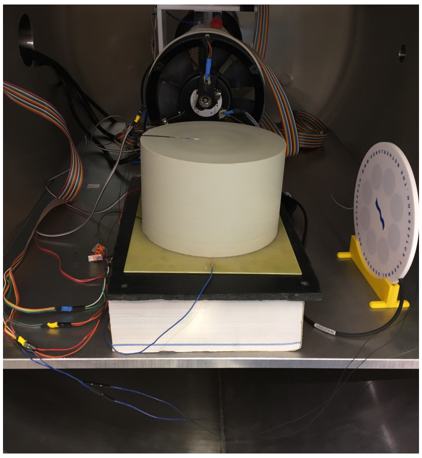

Figure 4.1: First system set-up.

Figure 4.2: Hermetic tank where first set-up is placed.

The system is composed of three different layers:

- The bottom includes a heavy book and a rectangular rubber surface to separate small system temperatures from tank metal.
- The middle is formed by a PCB (Printed Circuit Board) designed to produce constant heat.
- The top part consists on a polypropylene cylinder.

The idea is to create a constant heat flux to measure, so constant heat flux generated from PCB will go through cylinder and this will be measured by the thermopile placed on its top.

It is really important to consider each dimension to generate heat only where it is necessary, thats why both the PCB and the cylinder have a radius of 81.5 mm, very similar to HFP03 thermopile radius. Cylinder height is of 105 mm to assure a small heat flux to measure.

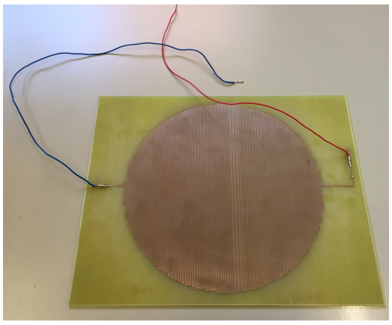

Figure 4.3: PCB used to produce constant heat.

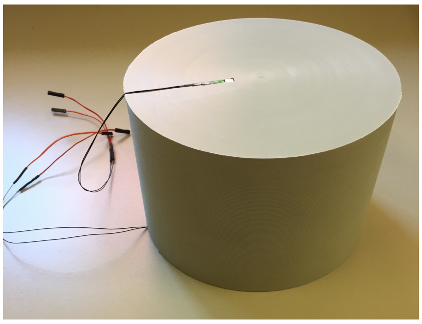

Figure 4.4: Cylinder model view.

It is important to know heat flux generated through cylinder to check if it is the same or similar to the one obtained in thermopile output. In order to measure it is necessary some device that gets the temperature in bottom and top cylinder surfaces but doesn't affect to system values. Considering these requirements, two pt500 (500 ohm platinum resistor) are utilized in the places where temperature is needed. It is seen in Figure 4.4 that cylinder surface has an specific hole for it.

Thermopile temperature for the second control is needed so a third pt500 is used for it and pt100 (100 ohm platinum resistor) is introduced to the system to observe ambient temperature.

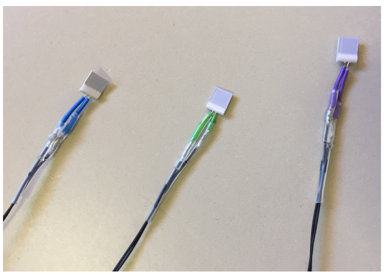

Figure 4.5: Pt500 set-up.

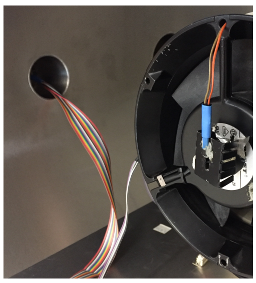

Figure 4.6: Pt100 configuration to measure ambient temperature.

On the left is shown an image of the third pt500 stuck on the HFP03 top plate and on the right the vertical support designed with a 3D impresor used in every sequential test with the HFP03.

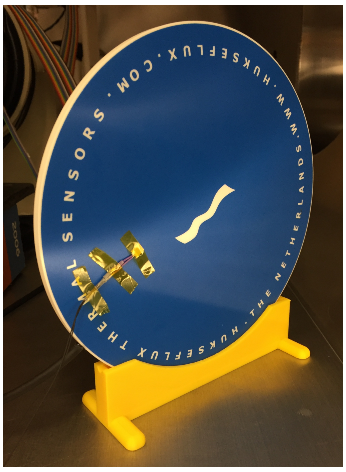

Figure 4.7: HFP03 top plate.

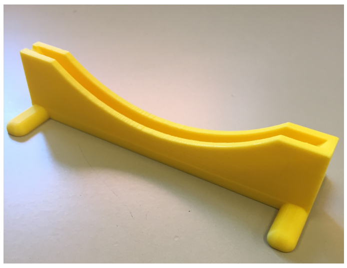

Figure 4.8: HFP03 thermopile support.

Finally, second system set-up that includes HFP01 thermopile is shown below:

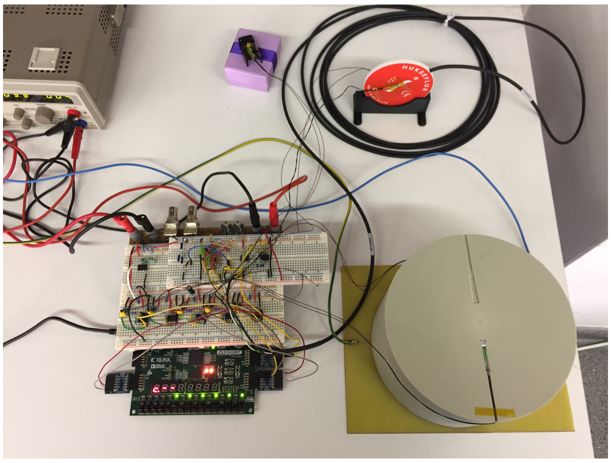

Figure 4.9: Second system set-up.

This system software needs to know both top and bottom thermopile temperatures. For that reason, only differences between systems set-up are top cylinder surface that has two holes, HFP01 has a pt500 stuck in both plates and it isn't placed inside an hermetic tank. Another equal vertical support with HFP01 dimensions has been printed.

4.2 System implementation using LabVIEW

First implementation was taken in LabVIEW due, as it has been exposed before, to a software that seemed really useful and user friendly designed for another project that also worked with differential measures and that needed to determine temperatures using platinum resistors.

Using an hermetic tank is very useful but complex. It was necessary to prepare a new connection cable for inside tank wall to ensure that each system set-up component (3 pt500, 1 pt100, thermopile output, PCB ground and source) was connected to its both equivalent pins (National Instruments adaptor input and output).

LabVIEW environment has as inputs the thermopile voltage, thermopile top temperature, cylinder top and bottom temperatures and ambient temperature. Its outputs are the injection of 1 mA of current to each platinum resistor and the controlled current value injected to the thermopile.

Below there is explained the controls functioning and system limitation:

- **Control 1**

  This one as has been exposed in 2.1 Previous study consists of ensuring that a constant gradient is being enforced at the thermopile. In order to achieve it the percentage of intensity injected is controlled by a PWM (Pulse-Width Modulation) that increments its duty cycle one step if target value is higher and decrements it if is smaller. All values needed to perform it are thermopile output and its target value.

  Next equation (2) shows the condition that control 1 takes into account in deciding to increase or decrease its percentage injection:

  $$\Delta V_{out} = V_{+} - V_{-} = \Delta V_{target} \tag{2}$$

  Target voltage value is controlled comfortably with a Numeric Control in LabVIEW user interface. This software that allows the user to change its target instantly and efficiently just is able to inject current in one direction. In this way, achieving target value needed of 0 V only injecting positive or negative intensity is impossible, so target values range in this system has been of some mV (from 1 mV to 10 mV).

  The inability to inject negative currents in the thermopile has been an important limitation because it does not allow this first control to be carried out as planned. Altough this problem, it seemed that good results were being obtained in this way so it is when a new system version is proposed.

- **Control 2**

  Second condition to reach is that the temperature at the bottom of the thermopile is as a close as possible to the temperature at the top cylinder surface. All values needed to perform it are thermopile output, thermopile top temperature ($T_{top\_thermopile}$), cylinder top temperature ($T_{top\_cylinder}$) and HFP03 sensor thermal resistance equal to $71 \cdot 10^{-4}$ K/(W/m^2).

  In order to achieve it a significant change in software was needed. Due to system limitation found I decided that working in the new system version was more important, so PWM period left fixed and not variable like control planned. Finally, this second control consists in intensity quantity injected and not in injection time. If target value is higher than thermopile average temperature it increments 0.1 mA the intensity injected to a maximum of 5 mA and in the opposite situation it decrements it 0.1 mA to a minimum of 1 mA.

  Next equation (3) shows the condition that control 2 takes into account in deciding to increment or decrement current quantity:

$$T_{average} = T_{average_{target}}$$
$$T_{top\_thermopile} - \phi_{out} \frac{71 \times 10^{-4}}{2} = \phi_{out_{target}} \frac{71 \times 10^{-4}}{2} + T_{top\_cylinder} \tag{3}$$

To sum up then, the waveform that both controls have been worked with is shown in the figure below: Both controls working together gives a control

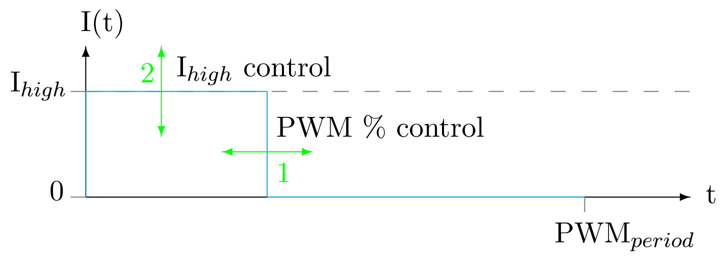

Figure 4.10: Pulse-width modulation controls in LabVIEW.

1 well functioning and a control 2 saturated. As first control decides the injection percentage, when second control needs to inject lot of current the

first one decrements too much the duty cycle. It makes them go into conflict and no solution is found.

4.3 System implementation using FPGA from scratch

This second implementation was needed due to important limitations found in the first system. The objective, now that hardware and software were designed from scrach, was to apply exactly the controls proposed.

So as to fulfill requirements this new set-up includes the simulated control algorithm converted to VHDL and implemented in a FPGA and ADC's to connect to a complex analog part carried out in two protoboards.

- Concerning to FPGA inputs and outputs: as outputs it has two pointers P_1 and P_2 that describe PWM control and as inputs it has the same data as the first sytem but with one extra value, thermopile bottom temperature is also obtained.
- Analog design includes a Howland current source which positive and negative inputs are controlled by two FPGA output pointers P_1 and P_2 to inject positive or negative current to the thermopile according to controls decision. It also incorporates the current source to excite each platinum resistor, the voltage divider needed to measure their value and a thermopile output amplification stage implemented due to small HFP01 sensitivity of $60 \cdot 10^{-6} V/(W/m^2)$.

Moreover, a communication between FPGA and PC to send data obtained is implemented using serial COM connections.

During this set-up implementation also some problems were found but all of them were overcome.

- The first one observed was that increasing Howland source resistor which controled output current value produced non expected oscillations in the current source. So at first only small intensity values were able to be injected to the thermopile which were not enough to control average temperature.

  It was detected that the problem was from another part of the system. Howland current source implemented worked correctly with a maximum output current value of 30 mA. The oscillation was being introduced due a negative current saturation of intrumentation amplifier output. That's why changing the resistor that was affecting to this part was suficient to finish with oscillations.

- Other oscillations were detected from controls implementation. The simulations proposed a sigma-delta control which was not lineal, it works with a variable structure that changes depending on the thermopile voltage for gradient control and over the temperature difference between the cylinder top surface and thermopile average temperature for average control.

  It was decided to switch to another controller based on sliding mode. In the next figure its scheme is shown:

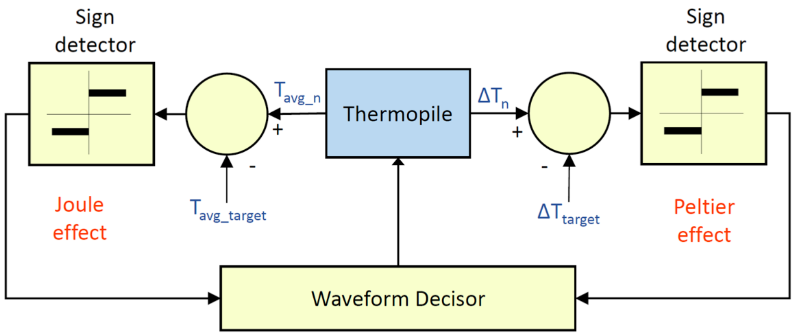

Figure 4.11: Sliding mode control approach

The following figure shows all PWM's that can be described by the pointers and in which case is used each of them:

Its use is logical, for example when the thermopile temperature average is small PWM with higher period are needed to warm it and in the opposite situation a shorter period that ensure the gradient control but decrease its general temperature.

4.4 Obtained data processing

From all data obtained in each system a processing part is necessary to obtain the results or information looked for.

Data direct processing won't be described. This case can be the one of platinum resistors temperatures at the moment to obtain its value in °C or concerning to FPGA its ADC input conversion for the voltage values measured.

So here below the most relevant calculations are going to be exposed. They are the ones applied to obtain heat flux through cylinder and heat

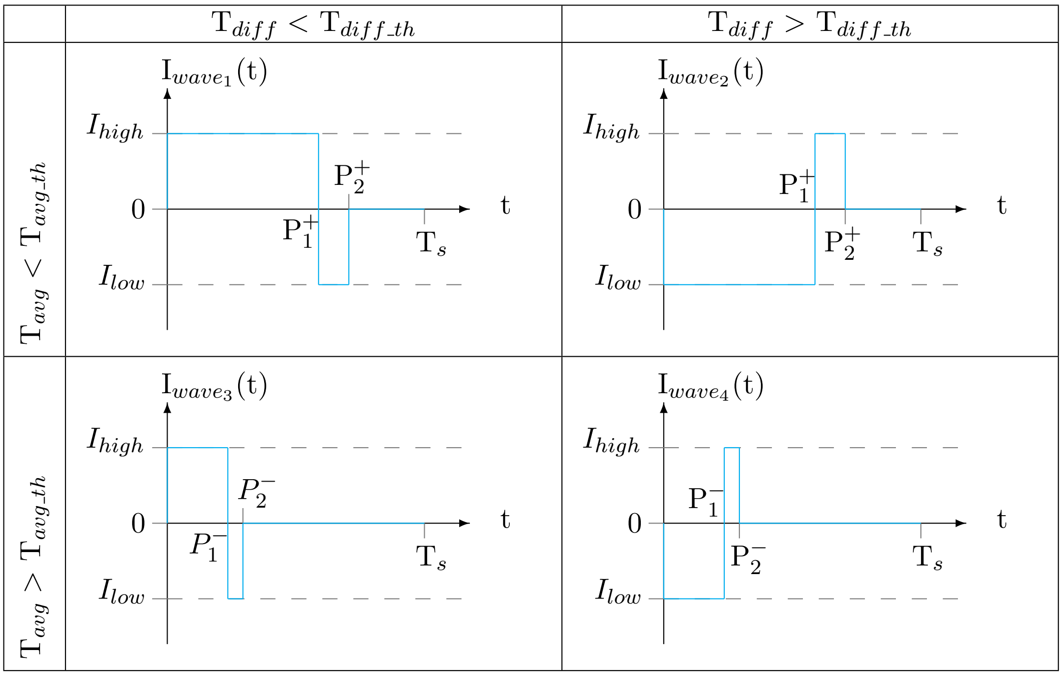

Figure 4.12: Current waveforms injected to the thermopile.

flux generated from controlling in both systems.

- **Obtention of heat flux through cylinder:**

  It is known that heat flux can be achieved knowing the heat transfer coefficient and temperature difference. Next equation shows the use of this formula in our system calculations.

$$\begin{gathered}\phi = h_c \times \Delta T \\ \phi_{cylinder} = \frac{\lambda_{PP}}{L_{cylinder}} \times (T_{bottom_{cylinder}} - T_{top_{cylinder}})\end{gathered} \tag{4}$$

  where

h_c	:	Heat transfer coefficient
λ_{PP}	:	Polypropylene thermal conductivity
$L_{cylinder}$	:	Cylinder height

- **Heat flux generated from controlling:**

We are able to derive the heat flux value of controls by the use of Seebeck coefficient, current density through thermopile and bottom thermopile temperature.:

$$\bar{\phi}_{control} = S \times \bar{J} \times T_{bottom_{thermopile}} \tag{5}$$

where

S : Seebeck coefficient
J : Density current

Each system setup as it is being using different thermopiles has its Seebeck coefficient and current density calculation:

- LabVIEW system:

$$S_{HFP03} = 68 \times 10^{-3} V/K$$
$$\bar{J} = \frac{\bar{I}}{A_{HFP03}} = \frac{I_{high} \times \%_{PWMcontrol}}{A_{HFP03}}$$

- FPGA system:

$$\begin{aligned} S_{HFP01} &= 8.5 \times 10^{-3} V/K \\ \bar{J} &= \frac{\bar{I}}{A_{HFP01}} \\ \bar{I} &= [\%_{grad} \times \bar{I}_{wave1} + (1 - \%_{grad}) \times \bar{I}_{wave2}) \times \%_{avg} + \\ &+ (\%_{grad} \times \bar{I}_{wave3} + (1 - \%_{grad}) \times \bar{I}_{wave4}) \times (1 - \%_{avg})] \end{aligned}$$

5 Results

In this section final results obtained would be presented and analyzed. It will cover both open loop and closed loop control response graphs, so here there would be observed and quantized the improvement in the transient response by using the second system set-up.

5.1 Open loop

In the following graph the open loop system response can be seen:

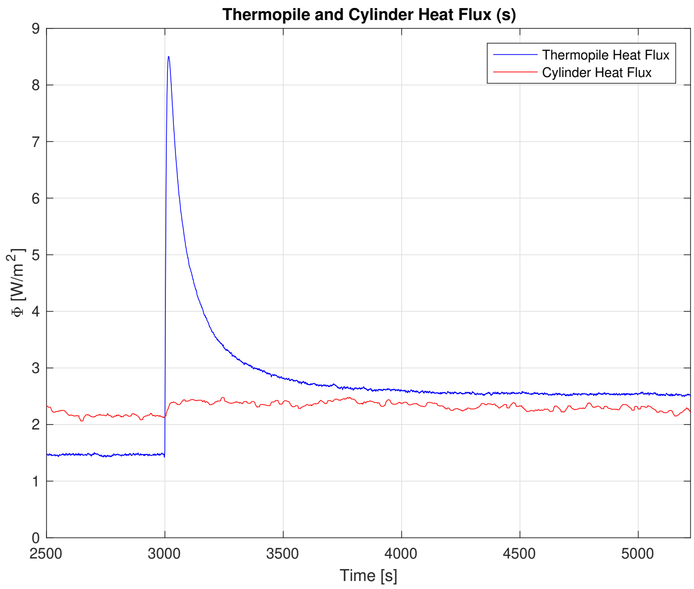

Figure 5.1: Heat flux open loop measurement.

This shape is obtained because is at 3000 s when the thermopile is placed in cylinder top surface so this big temperature difference generates a peak in the heat flux measured that will need time to give the real heat flux through the cylinder. That's why the red shaped is ploted to, this shape allows us to know when the system is obtaining the real heat flux and so its stabilization time.

From this result it can be observed a slow response of the open loop system as it was expected from simulations. Lots of test with larger system transient were obtained before this one, this seemed to has the shorter response that can be achieved with our system set-up. Despite being the best measure in open loop it still having a settling time greater than 600 s.

5.2 Closed loop

In the following graph the closed loop system response can be seen:

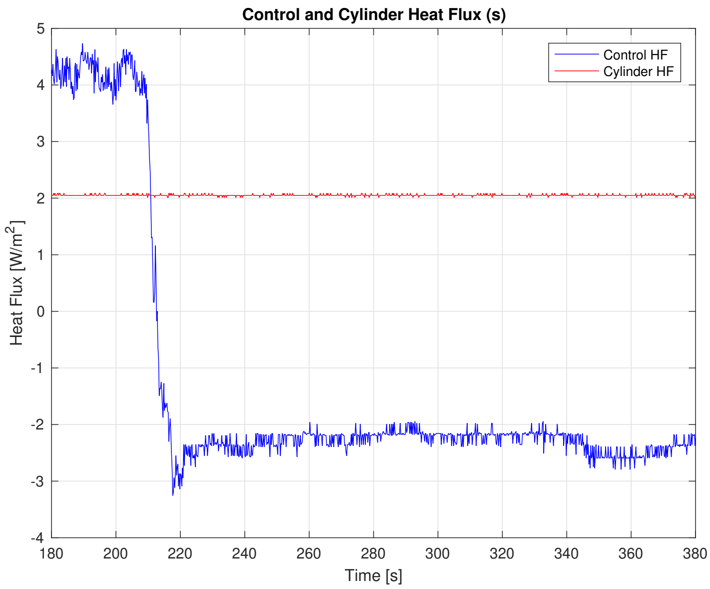

Figure 5.2: Heat flux closed loop measurement.

In the closed loop result the thermopile is placed in cylinder top surface at the second 210. Average control ensures the matching between cylinder top surface and thermopile average temperature and at the same time gradient control compensates temperature difference between bottom and top thermopile surface regulating the injected current.

It can be appreciate that almost a heat flux constant value of -2 W/m^2 is achieved really fast. As the target value of the thermopile is 0 W/m^2 every negative value will be compensating the positive real one. It is known that the result is correct thanks to red shape that shows constant cylinder heat flux of 2 W/m^2 to be measured.

Following there is observed a zoom from the previous closed loop response:

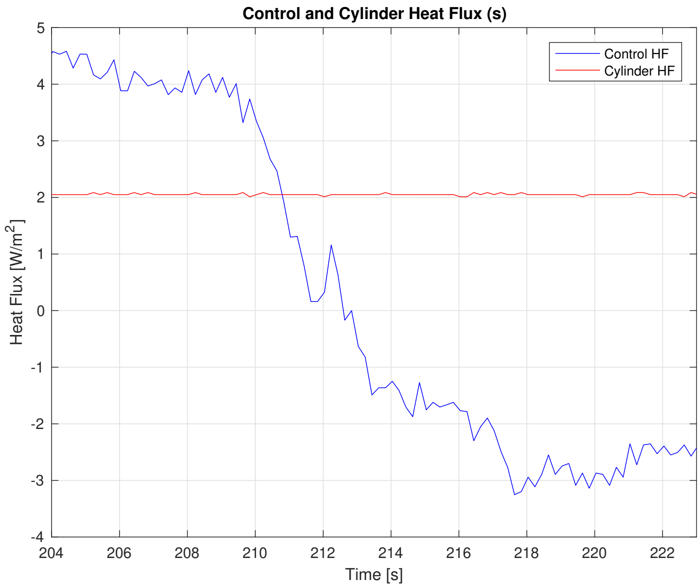

Figure 5.3: Zoom from heat flux closed loop measurement.

It is clearly observed that this zoom encompasses the instants before placing the thermopile to cylinder surface till the moment that it gets again a constant value so stabilization is finished.

Looking at both graphics above can be concluded that the stabilization time has decreased from 600 s to around 10 s.

6 Conclusions

The main objective of this work has been to prove experimentally that a significant reduction of the time response in thermopiles is possible. To this effect a specific setup has been designed in order to be able to generate arbitrary heat fluxes while at the same time being able to measure them on real time.

Additionally, two electronic setups have been used to test principal hypothesis. The first one, based on LabView, has allowed a first order control of the heat flux on the thermopile, while the second one has allowed two simultaneous controls that have improved the time response by a factor 100.

The main conclusion of this work, therefore, is that the expected time response reduction, as predicted by theory and simulations has been achieved. Based on these results a paper is being written for a JCR journal. The author of this TFG is an author of this paper.

This project has englobed very differentiated themes. They include understanding thermal systems behaviours, work with analogic and digital electronics parts, control theory and all its execution cover. Consequently lots of new knowledge related to electronics and methodology of work have been acquired. When performing a project that includes parts to integrate the fact of be conscient of each change and step followed is very important.

To sum up, taking this project has been a big chance. Thanks to all challenges that have been faced I had the opportunity to grow up as an electronic while maturing as a person.